Variability in UTH and Water Cycle Dynamics

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INTRODUCTION

There appears to be a disconnect between the mechanisms theoretically supposed to provide water vapor to the upper troposphere in the tropics and subtropics, and the mechanism that is most prominent in GCMs. In many GCMs, there is a strong cancellation between upper tropospheric moistening via the large-scale circulation, and drying due to compensatory subsidence from convection. A substantial net moistening effect arises from vertical transport of moisture by eddies, a mechanism that is completely ignored in most theoretical discussions

A key region showing variability in upper tropospheric humidity (UTH) during ENSO events is the subtropical region of the North Pacific. Although this is a region of time-mean descending air in the upper troposphere, analysis of atmospheric data shows that water vapor is supplied to the upper troposphere by vertical flux within transient eddies. The transient eddy activity in this region is in turn modulated by the interaction of the tropical circulation with the midlatitude circulation. Midlatitude interactions with the tropics are greatest during boreal winter and spring when transient eddy Rossby wave activity with periods between 5 and 30 days is at a peak. During most cold events, tropical convection is confined to the far western equatorial Pacific and westerly winds are found in the upper troposphere throughout the central and eastern equatorial Pacific. This allows the opening of a "westerly duct" in the eastern Pacific and supports anomalously high transient eddy activity in the subtropics. Conversely, during most warm events, deep convection and upper-tropospheric easterlies are found over the central and eastern equatorial Pacific. This closes the westerly duct, diminishes transient eddy activity in the subtropics, and creates extremely dry conditions. We have been able to relate the extremes in the tropical average (30N-30S) time series of UTH to variations in the westerly duct. We find that extremes in the UTH tropical time series over the last 20 years are twice as likely to occur in the boreal winter and spring, when the westerly duct is open, versus boreal summer and fall. This dynamical mechanism provides a negative feedback on interannual times scales.

UTH TROPICAL INTERANNUAL VARIABILITY

Figure 1 shows a time series of UTH interannual variability (Bates et al. 2001; Bates et al., 1996) for the tropics (30N-30S) and the one-point correlation map of this time series. Although the first three harmonics of the seasonal cycle have been removed to construct the anomaly time series, the time series still contains considerable high frequency variability and a suggestion of very low frequency variability in the second half of the record. Examining the timing of the extremes, we find that two thirds of the extremes occur in the boreal winter and spring. The largest extremes are found to coincide with the ENSO warm event of 1982-83 and the cold event of 1989-90. The largest areas of positive correlation in the spatial map are found in the subtropics of the eastern Pacific Ocean. This is a region where past studies have found large variability of extratropical Rossby wave propagation into the subtropics also related to seasonal and interannual variability.

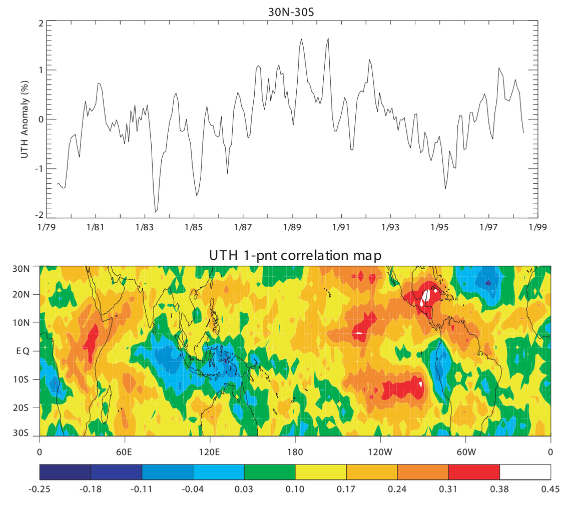

Figure 1

PROPAGATION OF MID-LATITUDE ROSSBY WAVES AND THE WESTERLY DUCT

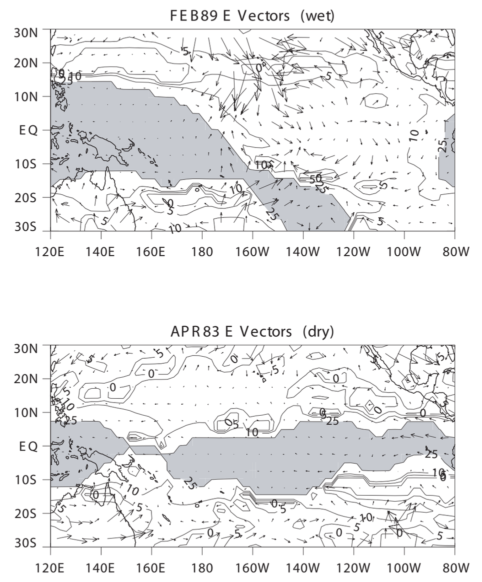

Figure 2

To examine the changes in transient eddy activity in this region during the large warm event of 1982-83 and the large cold event of 1989-90, we employed the dynamical analysis of 200 hPa winds as outlined in Kiladis [1998]. The horizontal E vector is a pseudo-vector constructed by calculating time-mean covariances between the perturbation zonal, , and meridional, , wind components:

$$\bar{E} = \left(\overline{v'^2 - u'^2}, -\overline{u'v'} \right) \quad (1)$$

The term $\overline{v'^2 - u'^2}$ is a measure of the mean anisotropy of Rossby waves. For example, if v'^2 is consistently larger than u'^2, the Rossby waves are preferentially elongated in the meridional direction and the E-vector points eastward. The term $-\overline{u'v'}$ is the negative of the time-mean northward flux of westerly momentum associated with perturbations. Together the two components approximate the preferred direction of the group velocity of the Rossby waves using suitable approximations, including the assumption of quasi-geostrophy. For this work, we use the NCEP re-analysis data and bandpass filter for 6-30 day transients.

Another useful diagnostic for representing the mean background state in which the transients are embedded is the stationary Rossby wavenumber:

$$K_s = \left(\frac{\beta_*}{\overline{U}} \right)^{1/2} \quad (2)$$

where

$$\beta_* = \beta - \frac{\partial^2 \overline{U}}{\partial y^2} \quad (3)$$

is the meridional gradient of absolute vorticity associated with the basic flow, $\overline{U}$ is the monthly mean 200 hPa zonal wind, and β is the meridional gradient of planetary vorticity. K_s is the total wavenumber at which a barotropic Rossby wave is stationary at a particular location in a given background zonal flow. Low values of the stationary Rossby wave number (below about 10) indicate regions of strong eddy activity and high values (above 15) indicate regions of weak eddy activity.

E-vectors and the stationary Rossby wavenumber were computed for all months and plots of the minima UTH (April 1983) and maxima UTH (February 1989) months are shown in Figure 2.

In the northern hemisphere, mid-latitude interactions with the tropics are greatest in boreal winter and spring when transient Rossby wave activity with periods between 5 and 30 days is at a peak. During strong cold events, such as 1989 (Figure 2), tropical convection occurs only over the far western Pacific Ocean since the western Pacific warm pool shrinks and moves to the west during cold events. In the tropical upper troposphere near the equator, this creates strong westerly winds in the outflow from this convection over the central and eastern Pacific. This allows the opening of a westerly duct in the eastern Pacific and supports propagation of Rossby waves deep into the subtropics [Webster and Holton, 1982]. This is evidenced in Figure 2 where values of stationary Rossby wave numbers less than 10 are found in the regions between the dateline and the west coast of South America. Large values of E-vectors pointing toward the equator near Hawaii are indicative of equatorially-propagating Rossby waves from the mid-latitudes into the subtropics. As shown by Kiladis [1998], the Rossby waves then propagate to the east and are associated with large plumes of moisture extending from near Hawaii to the U.S. west coast sometimes dubbed the 'pineapple express'.

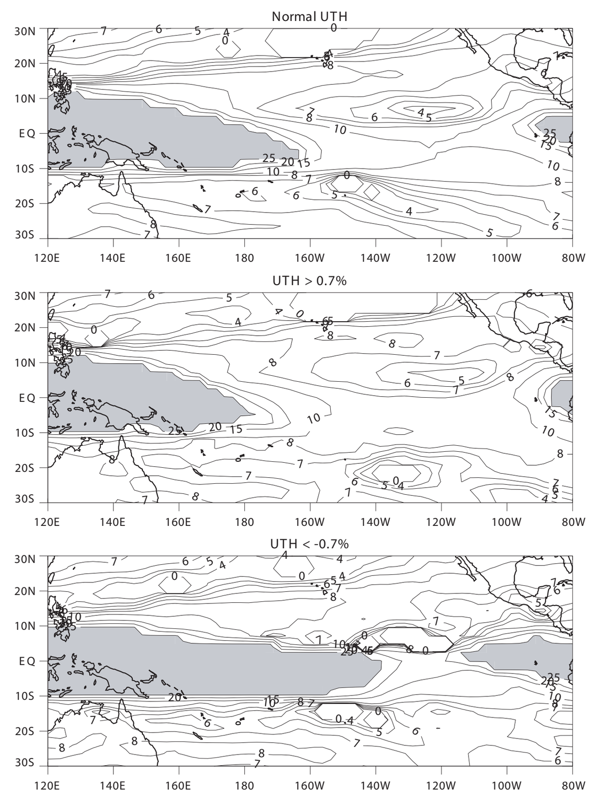

Figure 3

Conversely, during the large warm event of 1982 (Figure 2), deep convection extends far to the east in the equatorial Pacific Ocean. Upper tropospheric westerlies over the equator weaken dramatically or even reverse in the central and eastern Pacific. This is confirmed by calculations of the stationary Rossby wave number for these events. Large values of the stationary Rossby wave number are found over the eastern tropical Pacific, effectively shutting down the westerly duct. Virtually no E-vectors pointing toward the equator are found in this month, indicating an almost complete absence of Rossby waves in the subtropical North Pacific.

We examined the statistical characteristics of the relationship between the UTH extremes and Rossby wave activity by computing the seasonal mean Rossby stationary wave number. We computed the mean of all months within the season for only those months within the season with tropical average UTH anomalies greater than 0.7% and UTH anomalies less than -0.7%. For the boreal spring season (Figure 3) and the boreal winter season (Figure 4), we find low values of the stationary Rossby wave number extend further west versus the mean along the equator when UTH anomalies exceed 0.7% (Figure 3) and are found further east when UTH anomalies are less than -0.7% (Figure 3). The situation is similar for the boreal winter season. Thus, the westerly duct is larger when UTH anomalies exceed 0.7% and is much smaller when UTH anomalies are less than -0.7%. Figure 5 illustrates the opening and closing of the westerly duct in the UTH data during the ENSO events of the 1980's. A broad dry region extending across the Pacific from 10N to 20N in January 1983 is associated with the closing of the westerly duct, whereas greater transient eddy activity contributes to the high UTH in the eastern Pacific in January 1989.

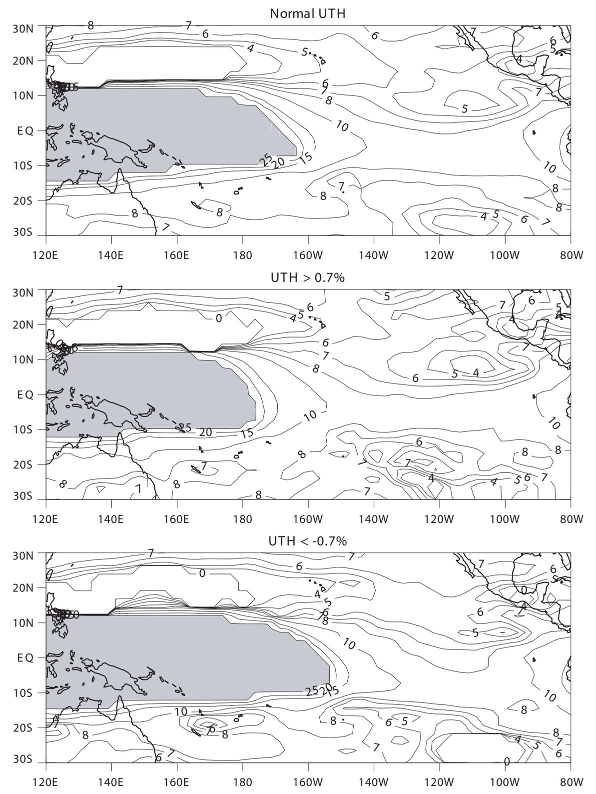

Figure 4

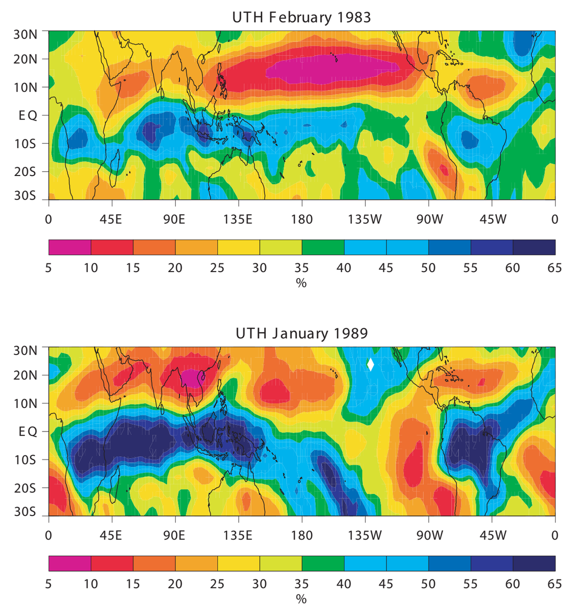

Figure 5

CONCLUSIONS

Atmospheric dynamical states, resulting from the interaction of the tropics with the mid-latitudes during boreal winter and spring, are responsible for most of the observed extremes in the tropical UTH time series. These states are referred to as the westerly duct in the eastern Pacific Ocean. The two extreme states of the westerly duct, and their influence on UTH, are illustrated schematically in figure 6. During extremes of high UTH, strong westerlies flowing out from deep convection in the western equatorial Pacific create a long fetch of westerlies over the equatorial eastern Pacific. This opens the westerly duct and allows Rossby waves (strong eddy activity) to propagate into the subtropics and re-hydrate the subtropical upper troposphere. Conversely, when deep convection extends into the central and eastern Pacific, westerly winds over the tropical eastern Pacific are weak and Rossby waves are blocked from propagating into the subtropics (no eddies).

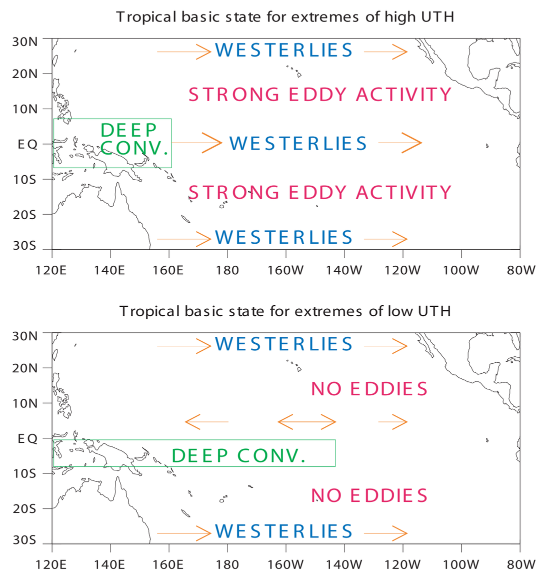

Figure 6